

Antineutrino monitoring for the Iranian heavy water reactor

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In this note we discuss the potential application of antineutrino monitoring to the Iranian heavy water reactor at Arak, the IR-40, as a non-proliferation measure. We demonstrate that an above ground detector positioned right outside the IR-40 reactor building could meet and in some cases significantly exceed the verification goals identified by IAEA for plutonium production or diversion from declared inventories. In addition to monitoring the reactor during operation, observing antineutrino emissions from long-lived fission products could also allow monitoring the reactor when it is shutdown. Antineutrino monitoring could also be used to distinguish different levels of fuel enrichment. Most importantly, these capabilities would not require a complete reactor operational history and could provide a means to re-establish continuity of knowledge in safeguards conclusions should this become necessary.



FIG. 1. Satellite image of the heavy water reactor at Arak, Iran, May 2012. Image credit Digital Globe and Google Earth.

The IR-40 reactor in Iran is of particular concern, since the design thermal power of $40 \text{ MW}_{\text{th}}$ combined with the choice of moderator, heavy water, makes this reactor ideal for plutonium production for nuclear weapons [1]; a satellite image of the Arak reactor complex is shown in Fig. 1. Iran states that this reactor will be used for the peaceful purposes of isotope production for medical uses and scientific research. It remains to be seen whether Iran will operate the reactor at all and, if the IR-40 becomes operational, whether it will operate as designed or with some modifications that make it less amenable to weapon plutonium production [1], or whether an extra-territorial siting arrangement might allay proliferation concerns [2].

If the IR-40 goes into operation, the IAEA will need to

confirm that its operations are as declared, using a combination of methods that are reliable and cost-effective. Antineutrino monitoring could complement other methods and provide important additional assurance to the international community that Iran continues to honor its commitments. Existing safeguards methods are ill-suited to deal with possible break-out scenarios or situations when inspector access is intermittent. The historic example of the Democratic People's Republic of Korea (the DPRK) and its interactions with the IAEA and the international community from 1992-1994 included both intermittent denials of inspector access and the DPRK's eventual break-out from the NPT. As a result, the question of plutonium production in the DPRK prior to 1994 is still unresolved, see for instance Ref. [3].

Antineutrino monitoring was first proposed more than 30 years ago [4] and is based on the fact that the number of antineutrinos produced and their energy spectrum depends in a well-defined manner on the reactor power and on the relative contribution to fission from the various fissile isotopes: uranium-235, plutonium-239, uranium-238 and plutonium-241. In a recent analysis [5] we were able to show that the application of antineutrino monitoring would have been able to provide timely information about plutonium production in the DPRK – even given the actual, constrained and intermittent access by IAEA inspectors. We have applied the techniques developed in Ref. [5] to the specific case of the Arak IR-40 reactor in Iran to show that antineutrino detectors could provide the IAEA with a resilient high-level monitoring capability not offered by any other known technique.

The IR-40 is capable of producing 10 kg of weapon-usable plutonium per year. A safeguards regime for the IR-40 must be able to verify that the actual plutonium production agrees with the declarations made by Iran,

and that the plutonium produced remains accounted for. Obtaining plutonium from most reactors and in particular from the IR-40, requires the reactor to be shutdown for the irradiated fuel to be removed. To quantitatively address the diversion problem involving plutonium from a known reactor, two questions have to be distinguished: the total amount of plutonium produced in the reactor and the amount of plutonium actually residing in the reactor core. The former can be inferred from the complete power history of the reactor, whereas the latter requires additional detailed information on the fueling history of the reactor or a method to directly assess the core state in terms of average fuel burn-up. It is the agreement or disagreement of these two quantities, the total produced and actual core plutonium, which may indicate whether or not a plutonium *diversion* has taken place.

The power history of a reactor¹ can be inferred by measuring the primary coolant flow rate and temperature drop using a thermo-hydraulic monitoring system, a method the IAEA already employs in some research reactors [6]. The core burn-up is not usually measured directly but is inferred from knowing the type of fuel that goes into the reactor core and on a burn-up calculation based on the power history of the reactor. For discharged fuel typically only the fact that individual fuel elements emit intense ionizing radiation is verified using Cerenkov light. The key to the relatively high reliability of this chain of inferences is to maintain continuity of knowledge by employing containment seals and surveillance measures.

Once continuity of knowledge is lost, recovery is difficult and may be limited. More sensitive monitoring methods are available to detect complex removal scenarios, although these methods are seldom used because they require isolating individual fuel elements, require lengthy measurement periods, and are expensive to employ. Antineutrino monitoring could provide a robust and non-intrusive alternative method to recover from a loss of the continuity of knowledge.

Consider a hypothetical IR-40 example inspired by the historic DPRK record: assume that there has been full safeguards access for N-1 months but, in the Nth month, continuity of knowledge is lost. Assume further that the reactor is shut down at the beginning of the Nth month. There could be many reasons for such events to happen, spanning the gamut from legitimate operational reasons, to a mere technical glitch over a diplomatic stand-off, to an attempt at proliferation with a wide range of measures taken to delay detection and reprisal². In the Nth month

of our hypothetical IR-40 scenario, the power history is interrupted, but for a sufficiently short time such that the extra burn-up that could be achieved is very limited and therefore, does not play a major role. But did a refueling take place? – The basic task is to reestablish verifiable knowledge of the core state without being able to rely on a power record or uninterrupted containment and surveillance.

In Ref. [5] we showed that measuring the composite energy spectrum of antineutrinos emitted from a reactor could allow the burn-up and, thus, the plutonium content to be estimated accurately and in a timely manner. We make the same assumptions here about the detection system as in Ref. [5], i.e. 4.3×10^{29} target protons at a hypothetical efficiency of 100%, which translates to a detector mass of 10-15 t, once the actual efficiency and chemical composition are accounted for. We envisage a system where the whole detector with supporting electronics fits inside a standard 20' shipping container. Smaller detectors would also work but the times required to achieve the performance we cite would be correspondingly longer. Furthermore, we assume sufficient background rejection capabilities to allow for surface deployment. From Fig. 1 we estimate the diameter of the IR-40 reactor containment building to be approximately 34 m and therefore with the shipping container positioned right against the exterior of the reactor containment building, the antineutrino detector would be located 17.5 m from the center of the reactor core³.

Assuming the reactor is running at full power when inspector access is resumed, following the methods given in Ref. [5], the antineutrino emissions could be used to determine the core plutonium content and, thus, to also determine whether or not the reactor had been refueled during the period when the inspectors were not allowed access. This burn-up based analysis relies on standard reactor physics calculations made using commercially available software⁴. It provides a means to correlate the fission rates of the various fissile isotopes in the reactor core. For our hypothetical IR-40 example, we assumed that the core in its original configuration contained 10 t of natural uranium dioxide, and that the reactor ran at its design power of 40 MW_{th}. Our model was derived from a full three dimensional analysis developed by Willig, *et. al.* [8]. Our results in terms of isotopic composition for the major fissile isotopes and all of the main plutonium isotopes agree to within 1-2% with the corresponding values reported by Willig.

¹ Total integrated reactor power can also be used to estimate the production of tritium in the heavy water inventory.

² For an extended period without inspector access, secondary means of monitoring reactor operation, e.g., infrared satellite imaging, could detect reactor operation and provide a rough es-

imate of reactor power.

³ More precise distances could be obtained during design information verification activities at the IR-40.

⁴ We carried out a reactor simulation of the IR-40 using the two dimensional neutron transport analysis code NEWT and the depletion code Origen. Both codes are from the SCALE software suite [7].

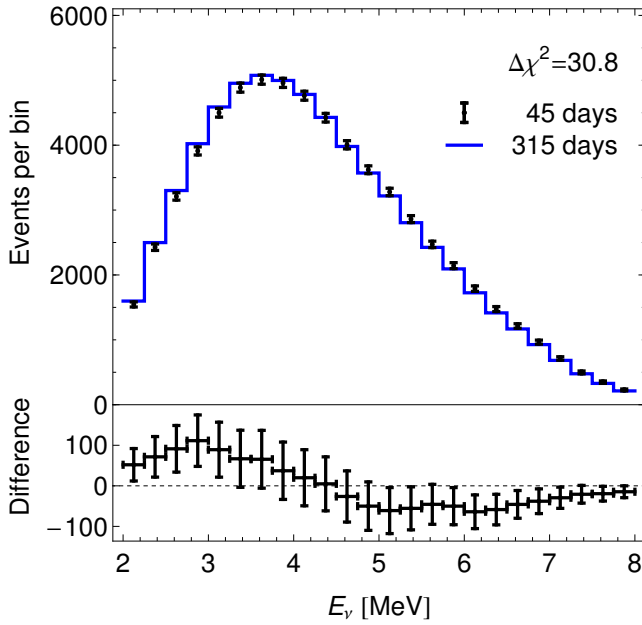


FIG. 2. In the upper panel, data points show the event rate spectrum obtained in a 90 day data taking period for a core of average age of 45 days. The error bars indicate the statistical error in each bin. The blue line indicates the corresponding expected event rate spectrum for a core of average age of 315 days. The lower panel shows the difference in event rates between the 45 day core and the 315 day core and the corresponding statistical error bars.

In Fig. 2 we show the resulting event rate spectrum for a core of 45 day average age (data points with statistical error bars) and for comparison the expected event rates for a core of 315 days of age (blue line). Clearly, the older core has a much softer antineutrino spectrum, which is because of the much higher plutonium content as fission of plutonium produces a softer antineutrino spectrum. The difference in χ^2 between the two cores is 30.8 units corresponding to about 7 kg difference in plutonium content. The visibility of this effect does not rely on extremely good energy resolution since the spectral feature is essential bi-modal: below about 4 MeV the rate goes up and above it goes down.

The quantitative results of our IR-40 analysis in terms of plutonium content are shown in Fig. 3, where the vertical axis shows the amount of plutonium in the reactor core as a function of time. The blue curve shows the evolution of plutonium content assuming that no undeclared refueling has taken place, whereas the orange curve assumes that the previously irradiated core, containing 8 kg of plutonium, was replaced with a fresh core after 270 days of irradiation. Here, 270 days was chosen since according to Willig *et al.* the content of plutonium-239 drops to 93% after 270 days and thus 270 days represents the longest operational period that still yields weapon-

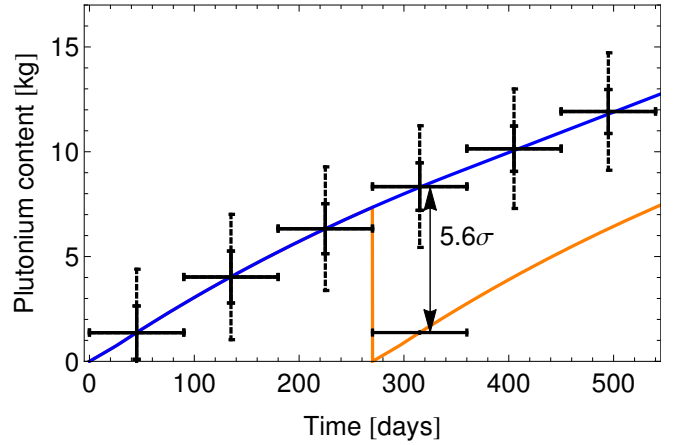


FIG. 3. Shown is the 1σ accuracy for the determination of the plutonium content of the reactor as a function of time in the reactor cycle. The data taking period is 90 days each. Dashed error bars indicate the accuracy from a fit to the plutonium fission rate f_{Pu} , whereas the solid error bars show the result of a fit constrained by a burn-up model. The blue line indicates operation without refueling and the orange line indicates operation with a refueling after 270 days.

grade plutonium⁵. Within the first 90 days of the putative IR-40 shutdown the two cases would be distinguished unequivocally by analyzing the antineutrino monitoring data. Even partial core refuelings corresponding to as little as 1.9 kg of removed plutonium could be detected at 90% confidence level. Alternatively, a full core refueling would be detected within about 7 days at 90% confidence level.

If the IR-40 remains shut down after the loss of continuity of knowledge, the antineutrino detector still offers a method to assess the core state by measuring the antineutrino emissions from the long-lived fission fragment isotopes: strontium-90 with a half-life of 28.9 y, ruthenium-106 with a half-life of 372 d, and cerium-144 with a half-life of 285 d. In the decay chains of these three isotopes, antineutrinos are emitted with sufficient energy to be detected by a standard antineutrino detector using inverse beta-decay. These long-lived fission fragment isotopes have direct fission yields in the percent range and thus their abundance is large and directly proportional to the burn-up of the fuel. By measuring these antineutrino emissions it could be possible to assess the approximate fuel burn-up and plutonium content, and to determine whether a major removal of spent fuel had taken place.

The measured antineutrino rates from these fission products would be much smaller than the antineutrino measurement rates during reactor operation. In Ref. [5] we estimated (based on data from [9]) that there will be

⁵ Even lower grade plutonium can be (and has been) used to make nuclear explosives and 93% does not constitute a sharp boundary.

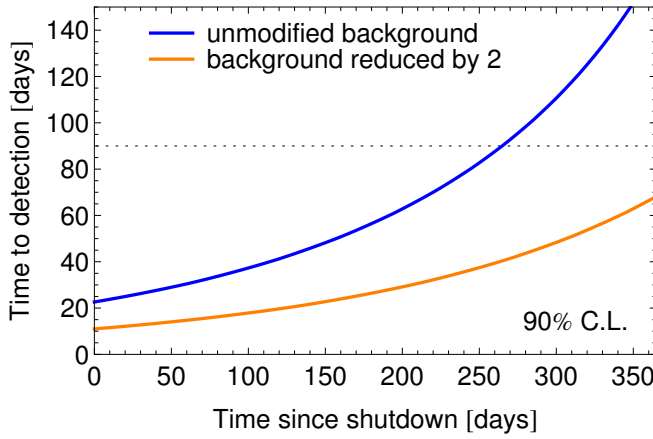


FIG. 4. Shown is the time required to achieve a 90% C.L. detection of defueling the reactor as a function of the time since shutdown when the defueling takes place. This calculation assumes a fuel burn-up corresponding to 270 d of reactor operation at nominal power of $40 \text{ MW}_{\text{th}}$. The different lines are for different levels of cosmogenic background suppression.

about 43 background events per day per tonne of detector from beta-delayed neutron emission from cosmogenically produced lithium-9 and about 1 background event per day per tonne from fast neutrons. In Fig. 4 we show the time required to achieve a 90% confidence level detection of removal of all the spent fuel contained in the reactor core as a function of the time since shutdown when the core removal occurs.

As previously stated, the size of the signal is proportional to the burn-up of the spent fuel, hence the longer the reactor has been running the easier this measurement becomes. Even in the low burn-up case, which would be characteristic for the production of weapon-grade plutonium, this measurement could be performed with current background rates for data taking as late as 250 days after shutdown. Or, in other words, if data taking starts within a month after shutdown, a 90% confidence level confirmation of the presence of the core can be achieved within 30 days or less. With a moderate improvement in background rejection by a factor of approximately 2, this measurement could succeed even a year after the shutdown.

Given the proliferation concerns regarding the IR-40, it has been suggested that the reactor could be modified to make it less suitable for the production of weapon-grade plutonium. One possibility would be to modify the reactor to use low-enriched uranium (LEU) instead of natural uranium (NU) as a fuel and changing the moderator from heavy to light water [1]. A detailed neutron transport reactor physics calculation has been reported by Willig *et al.* [8]. They concluded that changing the moderator from heavy to light water could be detrimental to reactor safety. Instead it has been proposed to use a heavy water moderator together with fuel enriched

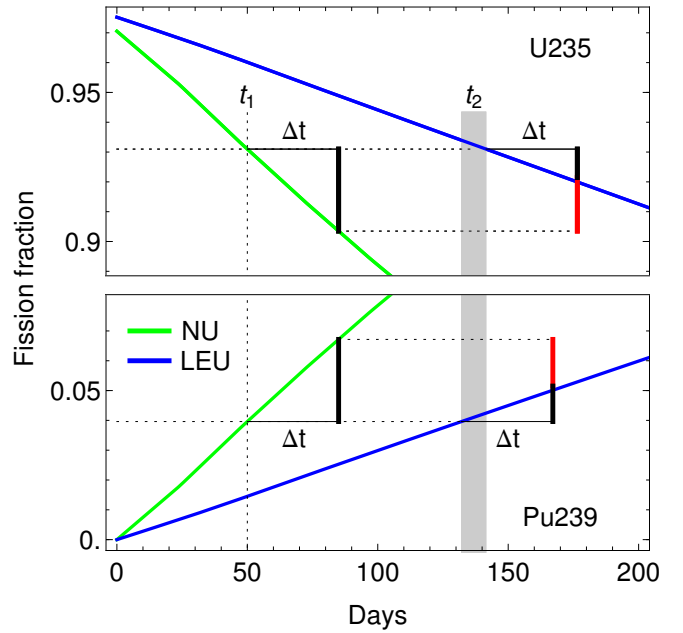


FIG. 5. Shown are the fission fractions in uranium-235, upper panel, and plutonium-239, lower panel, for a natural uranium fueled core (NU) in green and for a 3% enriched uranium fueled core (LEU) in blue as a function of time elapsed in the reactor cycle. The fission fractions in both isotopes at time t_1 for the NU core match those at a later time t_2 for the LEU core as indicated by the horizontal dashed lines. The change of fission fractions after a fixed time interval, Δt , the so called differential burn-up, is indicated by the thick vertical black lines. There is a distinct difference in differential burn-up between the LEU and NU cores for both isotopes as indicated by the thick red lines.

to 3%, providing a use for the existing Iranian stock of LEU. This LEU configuration could reduce the annual plutonium production from 10 kg to 3.9 kg with a slightly smaller fraction of plutonium-239.

If LEU fuel were introduced into the IR-40, antineutrino emissions could also be used to distinguish a natural uranium fuel core from a low-enriched uranium configuration by tracking the rate of change in the plutonium fission fractions in the reactor, a technique we term *differential burn-up analysis* (DBA). The basic observation behind DBA is that both configurations follow the same overall burn-up pattern: specifically, for the uranium-235 fission fraction, F_{U235} , and the plutonium-239 fission fraction, F_{Pu239} . Being on the same overall path implies that looking at a single snapshot in time, t_1 , the resulting single pair of values of $F_{U235}(t_1)$ and $F_{Pu239}(t_1)$ could not be used to distinguish the two configurations. This is illustrated in Fig. 5, where the time evolution of the fission fractions in uranium-235 and plutonium-239 is shown for both the NU and LEU cores. The pair of fission fractions $F_{U235}(t_1)$ and $F_{Pu239}(t_1)$ for the NU core is nearly identical to the pair $F_{U235}(t_2)$ and $F_{Pu239}(t_2)$ for the LEU core. This identity is approx-

imate since it would require two slightly different values of t_2 for uranium-235 and plutonium-239 to achieve exact identity, as indicated by the width of the gray vertical band. This effect is, however, too small to distinguish the two configurations. The speed at which both configurations move along this path is significantly different, therefore comparing the differential burn-up $F(t + \Delta t) - F(t)$, shown as thick vertical lines, for both configurations gives rise to a measurable difference between the NU and LEU cores, shown as thick red lines. Note, that the uranium-238 fission fraction does not contribute to this distinction since it stays constant for both core configurations and the plutonium-241 fission fraction is present only at a very small, basically unmeasurable level. Applying DBA to the case at hand we find a 90% confidence level distinction between the two configurations solely based on antineutrino measurements within about 160 days.

In summary, we have shown that if antineutrino monitoring of the Iranian IR-40 reactor were instituted, it could provide a complete assessment of the reactor core in terms of burn-up and plutonium content with a sensitivity exceeding standard IAEA verification requirements while meeting the timeliness criterion of 90 days. This information could be available in a timely manner and could be obtained by placing a detector outside the reactor building. This technique does not rely on a declaration of reactor power since the power could be inferred from the antineutrino signal simultaneously with the core state. In case the reactor is shutdown for extended periods, monitoring antineutrino emissions from long-lived fission products could make it possible to verify the presence of the spent fuel inside the reactor core for up to several hundred days after the shutdown. In combination, these techniques could allow a graceful and timely recovery from a loss of the continuity of knowledge. Furthermore, differential burn-up analysis could provide a means to distinguish different fuel enrichment levels. Other safeguards methods alone could not achieve this performance, and are likely to be more intrusive and labor intensive.

Antineutrino monitoring would work as well for *any* reactor from a few megawatts thermal power to small mod-

ular reactors to large scale commercial nuclear power reactors. Also, it can and should be combined with existing monitoring techniques to enhance effectiveness against a host of future possible developments.

While the results of theoretical analyses are promising, antineutrino reactor monitoring still faces the need for crucial R&D in terms of background rejection and rugged detection systems as well as a precise calibration of reactor antineutrino fluxes. Looking ahead, and noting Iran's willingness to extend IAEA access into aspects of its nuclear program that are not available in other states, Iran may itself wish for the IAEA to include antineutrino monitoring in the safeguards approach for the IR-40, providing a real-world opportunity for a full scale demonstration to enhance the credibility of the global non-proliferation system.

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